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Cover photo: An artesian well, belonging to catfish farmer Ronnie Pucek, in the Edwards Aquifer in 1993. © Peter Essick

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Groundwater Levels in Northern Texas High Plains: Baseline for Existing Agricultural Management Practices

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Abstract: New groundwater policies are being debated for the Northern Texas High Plains because of Ogallala Aquifer depletion. These policies should be evaluated using a calibrated groundwater model for assessing their impact on subsequent groundwater levels. The objective of this study was to calibrate and validate a regional groundwater model for predicting the impact of existing agricultural management practices on groundwater levels beneath 4 counties located in the Northern Texas High Plains. Results indicated that the MODFLOW-2000 groundwater model was calibrated and validated satisfactorily based on reproducing and comparing groundwater levels with coefficients of determination of 0.97 and 0.98, root mean square errors of 28.0 meters (91.9 feet) and 15.5 meters (50.9 feet). The model showed normalized root mean square errors of 6.9% and 4.3%, for calibration and validation, respectively. Analysis of prediction results indicated that 2 zones would become depleted if the current level of aquifer exploitation continues with no modification for the next 50 years. The calibrated model should assist water managers in evaluating alternative agricultural management policy scenarios.

Keywords: groundwater modeling; irrigation; MODFLOW; Ogallala Aquifer; water management

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Terms used in paper

Short name or acronym	Descriptive name
NPGCD	North Plains Groundwater Conservation District
TWDB	Texas Water Development Board
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

INTRODUCTION

Groundwater supplies are diminishing in multiple locations of the Ogallala Aquifer. Specifically, groundwater depletion in the Northern High Plains of Texas has been observed, and there is limited recharge to the aquifer. Irrigated crop production in the study area accounts for the majority of groundwater withdrawal. Reduction in water availability will reduce regional crop production that would impact the state, regional, and national economies. Policy-makers and stakeholders are considering ways to extend the life of the aquifer to maintain economic viability, and several strategies were identified via a stakeholder survey (Amosson et al. 2008). This region is key for securing a national food supply and for the Texas economy.

The Ogallala Aquifer is one of the largest and most productive groundwater resources in the world. It underlies an area of about 45 million hectares in the central United States covering parts of Texas, New Mexico, Oklahoma, Kansas, Colorado, Wyoming, Nebraska, and South Dakota. About 66 million cubic meters (or 66 gigaliters) of groundwater is withdrawn per day from this aquifer to meet agricultural and urban water demands (Maupin and Barber 2005). The Ogallala Aquifer sustains more than one quarter of the United States' agricultural production (Gurdak et al. 2009). The magnitude of agricultural water demand in this area makes water-use assessment critical in future planning efforts (Marek et al. 2009). The aquifer supports about $20 billion of production per year in the United States agricultural industry that includes 19% of wheat and cotton and 15% of corn produced (Qi and Scott 2010). The dominant land uses are rangeland (56%) and agriculture (38%) (McMahon et al. 2007). About 5.8 million hectares, or approximately 33% of agricultural land, has been reported as irrigated in eastern Nebraska, southwestern Kansas, and the west-central part of the Texas Panhandle (Gurdak et al. 2009).

Few regional aquifers have been studied as extensively as the Ogallala, and multiple computer models have been developed for the aquifer. Texas Water Development Board (TWDB) has supervised the most recent modeling efforts for the Ogallala Aquifer in Texas. These efforts have concentrated on assessing groundwater availability over a 50-year planning horizon. The North Plains Groundwater Conservation District (NPGCD) also determined desired future conditions for its district and adopted them in 2009 (NPGCD 2008a). The main purpose of Texas regional planning studies is to ensure the availability of groundwater supply and to evaluate water management strategies to further conserve groundwater. A regional modeling study, using a 1 mile x 1 mile (1,609 meter x 1,609 meter) grid, concluded that water from the Ogallala Aquifer could be greatly depleted by 2050 in 4 heavily irrigated counties (Dallam, Sherman, Hartley, and Moore counties) located in the Northern Texas High Plains (Dutton et al. 2001). However, there is a need to provide more detailed information. Therefore, a newer version of the MODFLOW model with higher resolution (800 meter x 800 meter) is presented in this paper. As a framework, a list of Ogallala Aquifer models prepared for Texas (Dutton et al. 2001) is presented in Table 1. This list was updated up to year 2010 to include the previous Northern Texas Panhandle model.

The objectives of this study were to 1) calibrate and validate a groundwater model using observed groundwater levels between 1937 and 2007 and 2) to define a baseline of the existing agricultural management practices on groundwater levels in the Ogallala Aquifer for the most intensively irrigated 4-county area located in the Northern High Plains of Texas. The general rationale for this study was the need to develop tools to help improve the understanding of impacts about water policies and new technologies that might affect water levels in the Ogallala Aquifer.

This study is a major component of a comprehensive regional analysis of the Ogallala Aquifer Program with the purpose of understanding short- and long-term effects of existing and

Table 1. Past modeling studies for the Ogallala Aquifer, which include partial or full areas of Texas.

YEAR	AUTHOR	MODELED AREA
1970	Claborn et al.	Parmer, Castro, Bailey, and Lamb counties (Texas)
1979	Bell and Morrison	Carson County
1982	Simpkins and Fogg	Texas Panhandle
1982, 1984	Knowles et al.	Texas High Plains
1984	Knowles	Texas High Plains
1984	McAda	Lea County (New Mexico), Cochran and Yoakum counties (Texas)
1984	Luckey	Central and Northern High Plains
1986	Luckey et al.	States: Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, Wyoming
1987	Luckey and Stephens	Southern High Plains of Texas and New Mexico
1993	Peckham and Ashworth	Texas High Plains
1995	Mullican	Roberts and Hutchinson counties (Texas)
1996	Dorman	Texas High Plains
1997	Mullican et al.	Southern High Plains
1999	Luckey and Becker	States: Oklahoma (Northwestern), Colorado (Southeastern), Kansas (Southwestern), New Mexico (Northeastern), and Texas (Northwestern)
2000, 2004	Dutton et al., Dutton	Northern Texas Panhandle
2003	Blandford et al.	Southern High Plains of Texas and New Mexico

alternative land use scenarios on groundwater level changes. The concern is that diminishing groundwater supplies will severely impact regional crop and animal production, which in turn will affect economic activity in the region. It is desirable to minimize adverse impacts on the regional economy due to the extensive future withdrawals of the limited groundwater resource.

STUDY AREA

This study is geographically limited to a 4-county area in the Northern Texas High Plains that includes Dallam, Sherman, Hartley, and Moore counties (Figure 1). The study area shares state borderlines with Oklahoma to the north and New Mexico to the west, and it occupies an area of 12,196 square kilometers (1.2 million hectares). In the Northern Texas High Plains, groundwater from the Ogallala Aquifer is the main source for agricultural and public water supplies that has sustained economic development in the region. Agriculture in the study region includes irrigated cropland, dryland cropland, and rangeland. Irrigated crop production for grain, fiber, forage, and silage accounts for 89% of groundwater withdrawals from the aquifer (Marek et al. 2004), and the regional economy is heavily dependent on the use of groundwater from the Ogallala Aquifer. Major crops are corn, cotton, hay, peanuts, sorghum, sunflower, soybeans, and wheat. According to the 2007 water-use survey summary estimates (TWDB 2007a), for the 4-county area during the irrigation season, 4 million cubic meters (or 4 gigaliters) of groundwater is withdrawn on average per day, and 3.9 million cubic meters (3.9 gigaliters) are withdrawn for irrigation purposes. The rest of the water is used for livestock, municipalities, manufacturing, mining, and power generation.

Historically, groundwater in this study area was not exploited extensively until the mid-20th century, even though some wells had been reported with records as early as 1919 (Musick et al. 1990). Irrigation development in the Texas High Plains began when farmers started drilling irrigation wells in the Ogallala Aquifer during the major drought of the 1930s. Yields of dryland crops were low at that time, and drought-relief financial assistance became available to bring new economic resources to the region. According to historical information, the aquifer was underexploited in land development for years before 1950. In the southern portion of the Texas

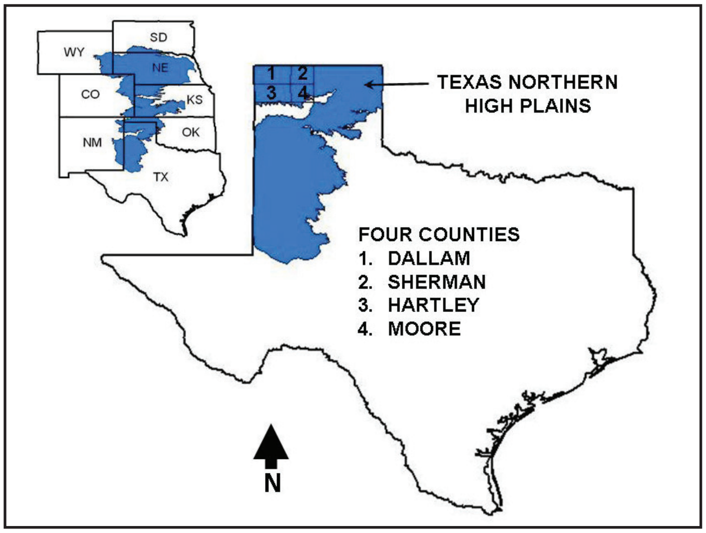

Figure 1. The Texas 4-county area of the Ogallala Aquifer region.

High Plains, rapid irrigation development began in the late 1950s and peaked in the late 1970s. In the Northern Texas High Plains, irrigation data gathered by Ouapo et al. (2012) demonstrated a peak in irrigation development in the late 1970s followed by a decline but then a higher peak in 2000. Center-pivot systems became more reliable allowing previously non-irrigated land to be irrigated. Thus, the analysis done for this study covers 2 unequivocal periods: the "predevelopment period" and the "exploitation period."

According to agricultural census data (NASS 2008), harvested cropland area has increased appreciably (by 64%) during the period of 1987–2007. Total cropland was 635,310 hectares in 2007 in the 4-county study area. About 42% of the total cropland (269,240 hectares) in the study area was under irrigation and about 80% of that was irrigated corn. This area contributes about 30% of the total corn production (81.6 megabushels or 2,073 gigagrams) in Texas (NASS 2008), and it is known for greater county-wide yields at 13.2 megagrams/hectare (210 bushels/acre) due primarily to the corn production being irrigated with practically no dryland corn production.

Hydrometeorology

The study area has an arid to semi-arid climate. Surface runoff is limited to the late summer season. The precipitation rate increases from 381 millimeters/year in the northwest to 483 millimeters/year in the southeast. Potential evaporation from free water surfaces ranges from 2,200 to 2,400 millimeters/year, significantly exceeding the precipitation rate and allowing little water for recharge to the groundwater system. Net recharge rates for the most recently calibrated groundwater model in the study region (Dutton et al. 2001) were less than 2% of precipitation. Annual average temperature ranges from 4 ^{o}C in January to 27 ^{o}C in July (NOAA 2009). The only surface water in the study area appears in ephemeral streams.

Geology

The Ogallala Aquifer is a remnant of a vast plain formed by sediments deposited by streams flowing eastward from the ancestral Rocky Mountains (Reilly et al. 2008) and is considered an unconfined aquifer (Gutentag et al. 1984). The Ogallala formation overlies Permian, Triassic, and Cretaceous strata and consists primarily of heterogeneous sequences of coarse-grained sand and gravel in the formation's lower part, grading upward into fine clay, silt, and sand. The sands are generally tan, yellow, or reddish brown, medium to coarse-grained, moderate to well sorted, and poorly consolidated to unconsolidated, although local cementation by calcium carbonate and silica occurs. The gravel is usually associated with sand, silt, and clay, and it is occasionally cemented (NPGCD 2008b).

The Ogallala formation in Texas was described by Seni (1980) as a series of coalescing, humid type alluvial fans for a depositional model. The Ogallala Aquifer is an exhaustible resource (Osborn 1973; Wheeler at al. 2006). No fractured rock zones and faults were identified within the study area, and some hydraulic continuity occurs between the Ogallala formation and the 2 underlying local aquifers, Rita Blanca and Dockum aquifers.

Rita Blanca Aquifer is a minor aquifer that underlies Ogallala Aquifer in Dallam and Hartley counties over an area of 2,400 square kilometers (TWDB 2007b) in the north-west vicinity of these counties. This aquifer is composed of coarse-grain sand and gravel layers of the Lytle and Dakota formations as well as in the Exeter Sandstone and Morrison formation. In some places, the Rita Blanca is also hydraulically connected to the underlying Dockum Aquifer. The Dockum Aquifer extends under 46 counties in Texas (TWDB 2007b) with a subsurface area of 57,000 square kilometers. The aquifer underlies Dallam and Hartley counties in their entireties and about 25% of Moore County (Figure 1). The Dockum Aquifer consists of sand and conglomerate inter-bedded with layers of silt and shale. The quality of water is generally poor because of salinity, hardness, and radioactivity, and does not meet drinking water standards in some locations. The water is, however, useful for irrigation, oil field operations, and municipal water supplies in other cases. The cross-formational flow between these local aquifers was not accounted for in the modeling for this study. According to the literature, flows between Rita Blanca, Dockum, and Ogallala aquifers have not been quantified. No studies were found to define this cross-formational flow, and there is consensus that multiple wells might be crossing more than 1 aquifer.

Hydraulic conductivity and specific yield are highly variable in this study area, and they do not follow any particular spatial tendency due to dependency on sediment types, which vary widely horizontally and vertically (Gutentag et al. 1984). Estimated hydraulic conductivity values are between 8 and 120 meters per day, and specific yield ranges from 2.5% to 27.5% (USGS 2008). Estimation of saturated thickness of the Ogallala Aquifer in the 4-county area (Hallmark 2008) indicates that maximum saturated thickness ranges from 15 to 140 meters with an average of 50 meters, and depth to groundwater level ranges from 15 to 137 meters. Aquifer base elevation varies from about 900 meters above mean sea level in the eastern edge of the study area in Sherman and Moore counties to about 1,400 meters above mean sea level in the north-west corner of Dallam County.

METHODOLOGY

The hydrologic simulations for this study were done using MODFLOW-2000 (Harbaugh et al. 2000), a computer program that solves the 3-dimensional groundwater flow equations through a porous media using a finite-difference method. A Visual MODFLOW Pro 4.3[1] (SWS 2008) interface was used to facilitate data input and resulting analyses. The main sources of data for this modeling effort include the U.S. Geological Survey (USGS), U.S. Department of Agriculture (USDA), TWDB, and the NPGCD.

Calibration and validation of the groundwater model for the study area were performed for 2 well-differentiated periods. During the first period (before 1950), the aquifer was considered to be in natural equilibrium based on the assumption that aquifer exploitation was not perceptible before 1950, and it will be referred as the predevelopment period. The second period (1950–2007) was the groundwater exploitation period for considering anthropogenic effects through time, and it will be referred as the exploitation period in this study.

Groundwater levels in the Ogallala Aquifer were predicted and evaluated differently for each period. We hypothesize that during the predevelopment period, Ogallala Aquifer water was discharged naturally through seepage into streams and springs when the aquifer was not able to hold the percolated water. Also, these discharges diminished during dry periods and natural groundwater levels remained almost constant until the next season, restarting the cycle. According to this hypothesis, the Ogallala Aquifer was naturally in equilibrium during the predevelopment period for modeling purposes (by obtaining recharge from precipitation and by withdrawing water by means of evapotranspiration from plants, stream flows, and spring discharge), keeping groundwater levels stable. The described hydraulic performance can be assimilated to a steady-state water flow, and it is represented by a steady-state aquifer model. The difference between aquifer behaviors for the exploitation period relative to the predevelopment period is the effect of pumping water from the aquifer by wells. In general, the naturally described processes for the predevelopment period continued to occur during the exploitation period. Groundwater usage during the exploitation period can be depicted as external actions that are applied to the aquifer resulting in non-equilibrium as a consequence. Those actions, combined with the natural response, generate variability in aquifer levels over time. This variability can be assimilated to a hydraulic transient-state, and it is represented by recreating a transient model for the aquifer.

Conceptual Model

A conceptual model has been created to represent the Ogallala Aquifer system beneath the study area to assess the effects of future groundwater exploitation on groundwater levels. The core information used to create the conceptual model was obtained from the USGS, USDA, the Ogallala Aquifer Program, TWDB, the Texas Natural Resources Information System, and NPGCD. Ancillary information was obtained from the National Agricultural Statistics Service, National Oceanic and Atmospheric Administration, Food and Agriculture Organization of the United Nations, and several Texas and Oklahoma institutions. Most information was originally on paper documents, printed maps, graphs, text files, and geographic information systems files. The soil structure and hydraulic properties were obtained from the USGS data repository (USGS 2008) with minor modifications to match NPGCD's red-bed layer data.

Boundary conditions were applied to cells located over the spatial limits of the computer model. Natural boundaries were preferred to artificial boundaries to make the model more realistic. Natural boundary conditions for the computer model included conditions present in nature and represent inherent aquifer characteristics. In contrast, artificial boundaries were defined to reduce computational expenses whenever natural boundaries were too far from the study area.

The conceptual model domain was extended beyond the 4-county area to reach the Ogallala Aquifer boundary to the south (Figure 2), to the west, and to about half of northern side of the region. The purpose of extending model boundaries was to decrease the length of artificial boundaries in spite of

[1] The use of trade, firm, or corporation names in this article is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Agricultural Research Service of any product or service to the exclusion of others that may be suitable.

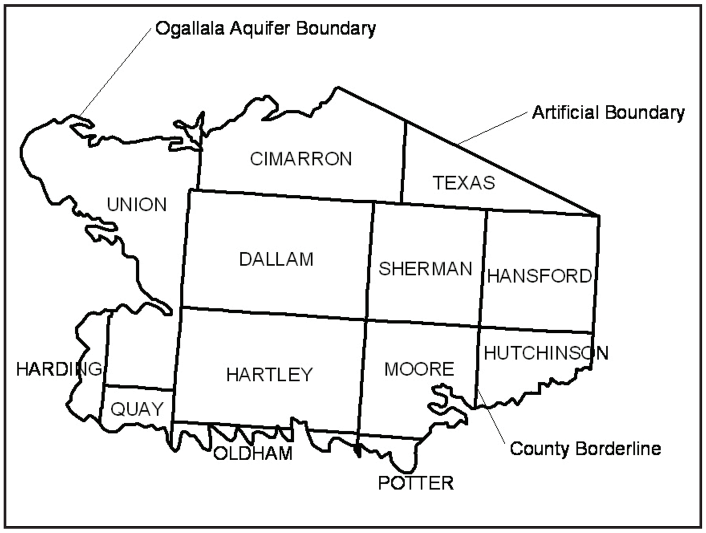

Figure 2. A delineation of boundary lines for the simulation.

increasing computing time, making the model more robust. Additionally, the straight-line border located to the north was simulated as a no-flow boundary because this groundwater flows approximately in the west-east direction (Gutentag et al. 1984) according to water table slope. The groundwater boundary was defined as a no-flow boundary condition. Historical spring data were obtained from a previous study (Brune 1975).

Artificial boundary conditions were defined for the eastern edge of the study area in the absence of natural boundaries. A general head-dependent flow boundary corresponds to a cell that flows from or to an external source proportionally to the head difference between the cell and the head assigned to the external source. For the eastern boundary and a portion of the north-east straight line, a general head boundary was defined. A general head-dependent flow was defined using different heads and distances to the external source depending on historic water table elevations. A general head boundary for the predevelopment period was 850 meters obtained from Gutentag et al. (1984). For the exploitation period, a general head boundary was defined at an elevation of 800 meters, which was adjusted during calibration process. Criterion applied to define distances from the study area boundary to the general head-dependent source was 3 times longer than the average depth of the aquifer in the boundary area.

The use of an 800 meter x 800 meter grid size for this study was partially based on considerations for future research, to accommodate similar or multiple pixel sizes from satellite imagery, and to efficiently use computational time. Each cell had internal, uniform characteristics for computational purposes.

Pumping for irrigation purposes is the primary mechanism used for aquifer discharge and precipitation is the main mechanism for recharge. Precipitation represents a small proportion of recharge due to the high evaporation rate from the soil and the high transpiration rate from plants. The distribution of recharge in the region is poorly known (Mullican et al. 1997). A need for further research on predicting recharge from precipitation and other variables was identified (Dutton et al. 2001).

A detailed study for the region by Luckey and Becker (1999) reported recharge rates of 16 to 24 millimeters/year for sand dune areas in Dallam and Hartley counties and rates from 1.6 to 2.1 millimeters/year for soils with low permeability in Sherman and Moore counties. More recent groundwater modeling studies (Dutton 2004; Dutton et al. 2001) of the Ogallala "n" model showed the necessity of increasing recharge rates in some areas in Dallam and Hartley counties by up to 10 millimeters/year and in Sherman County by up to 4 millimeters/year for modeling convergence. Therefore, recharge rates applied in this study ranged from 6 to 16 millimeters/year (2-3% of mean annual precipitation rate respectively), and they were applied to the uppermost active layer of the model in all cases. These recharge rates are greater than those shown in regional data that included the 4-county area (11 millimeters/year from Wood and Sanford 1995, and 10 millimeters/year from Dutton 2004), but they are feasible according to values reported by Luckey and Becker for sand dunes (16 to 24 millimeters/year).

The initial conceptual model considered uniform recharge rates of 5 millimeters/year and 11 millimeters/year over the study area, and the model never converged due to the generation of dry-cells in the north area of Union County, New Mexico (Figure 2). The model represented cyclic, dry-wetting conditions in some areas resulting in computational instability. To solve this issue, the model was divided into 5 identical layers. Additionally, dry cell wetting options were set to keep a minimum saturated thickness of 5 meters for the bottom layer, and the top 3 layers for Union County were set as inactive. Having the top layers inactive did not affect validity of the model because recharge was applied over the first active layer in the model, and this particular area was outside of the scope of this study. These conceptual model modifications allowed cells in the inactive zone to act as dry cells if the cells below the inactive zone were dry cells, too. Otherwise, these inactive cells were not involved in the computations, except for passing recharge water to lower layers.

Model Calibration and Validation

Calibration of the model was done to verify that the predicted groundwater levels closely corresponded to situations that matched the historical aquifer performance for an *a pos-*

teriori validation process. Multiple computer simulations were performed to match historical groundwater levels by means of parameter modification and conceptual model adjustment. Model calibration was performed for both the predevelopment and the exploitation periods. The model was calibrated for the predevelopment period by predicting and comparing groundwater levels of 1939 using a steady-state model, representing no change in land use and keeping all boundary conditions constant throughout the time. The model was calibrated for the exploitation period by reproducing and comparing groundwater levels using a transient model including 1 initial steady-state stress period. Hydraulic conductivity and recharge were the 2 sensitive parameters modified to improve matching of model predictions to historical water levels.

Data available for the predevelopment-period model calibration are sparse. Data from 15 monitoring stations were used to calibrate the model for predevelopment period. The calibration process for the predevelopment period was performed by comparing simulations results against measured groundwater levels in 1939. This year was selected as it is the earliest time that experienced little aquifer exploitation with relatively more data from monitoring wells (Figure 3). Hydraulic conductivity was adjusted, up to 1 order of magnitude, to reduce the differences between historical and simulated water levels for those zones where there were large discrepancies.

Every calibration simulation started with the first stress period as a steady-state and output from this steady-state model was considered representative of conditions for the 1950s. Output groundwater levels for the predevelopment time were used as an input for the first stress period in the transient model. Model calibration was accomplished for the exploitation period by comparing historical water level records with results from the model for the years of 1953, 1960, 1969, 1980, 1990, and 2000, which were selected for having a large number of observational records. Monitoring data were added to the model one at a time and results were analyzed before adding the next data series to the subsequent year in the analysis. This made 131 data points available for comparison. Data for the following year were added to the previous simulation after checking satisfactory results from the previous year. The parameters selected to improve matching results from the model to historical water levels were hydraulic conductivity and recharge as expected.

Model validation was performed by 1 simulation with no modification to the conceptual model or to the parameters by comparing results from the model with registered groundwater levels for the period 2001–2007. The year 2007 was the last year with available data during this study's simulation. Registered historical data from 22 monitoring stations located in the 4-county study area were used to validate the model. The model was validated for each year in the period of 2001–2007, and performance of the groundwater model was evaluated by comparing the predicted groundwater levels with the annually observed water table data. Statistics used for this purpose were the coefficient of determination (r^2), root mean square error, and normalized root mean square error, with a 95% confidence interval.

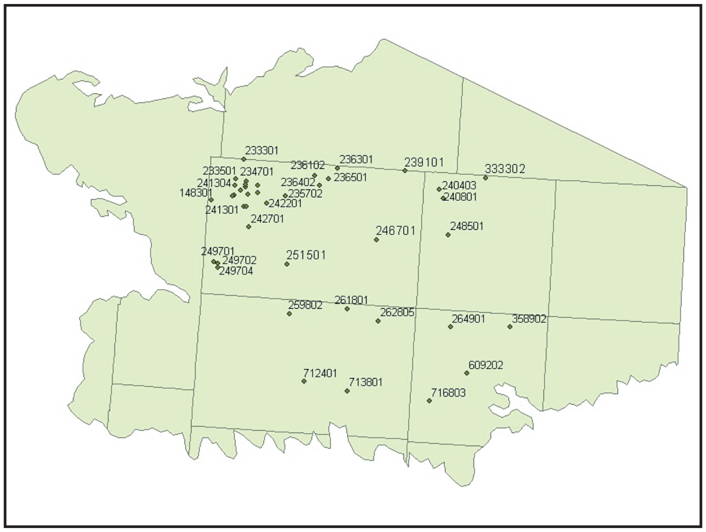

Figure 3. Locations of monitoring stations in the study area.

Modeling Current Agricultural Management Practices

The existing agricultural management practices were modeled to evaluate their impacts on groundwater levels by 2060, while assuming that future conditions are kept the same as current conditions. Future water demand was input to the validated model for simulating future groundwater levels based on a 50-year span projection. In order to simulate current practice, pumping rates were assumed constant during the period 2008–2060. Rates of groundwater withdrawal were computed for year 2008 by adding up pumping rates for each county for irrigation, municipal and public water supply, industry, manufacturing, and domestic and stock, totaling 3.3 million cubic meters per day for the 4-county area (Dutton et al. 2001). Water-use survey summary estimates (TWDB 2007a) were not used for this purpose as they are subject to continued revision. However, water demands used in this modeling effort corresponded to drought demands currently used by the TWDB for projection purposes. Water demand was spatially distributed using county average rates obtained from the same study (Dutton et al. 2001), and demand was distributed among the existing 5,881 registered wells. It was assumed that there would be no increment or reduction on the number of wells for establishing this baseline. The pumping rates were the only parameters added to validate the model for predictions.

RESULTS AND DISCUSSION

Artificial boundaries were minimized in length resulting in natural boundary conditions prevailing for the model. The grid size of 800 meters x 800 meters used for the entire area is the finest uniform resolution ever used for groundwater modeling in Texas to date. Model calibration and validation results are presented for both the predevelopment and the exploitation periods.

Calibration for the Predevelopment Period (1939–1950)

Groundwater levels for predevelopment time were reproduced by the model satisfactorily by simulating the groundwater levels in the Ogallala Aquifer in the 1950s, with a coefficient of determination of 0.99. Predevelopment, historical groundwater levels ranged from 955 to 1,405 meters above the mean sea level, and simulated groundwater levels for the same period ranged from 930 to 1,410 meters above the mean sea level in the 4-county study area (Figure 4). The model underestimated groundwater levels for some areas in Hartley, Moore, and south Dallam counties. By the contrary, the model overestimated groundwater levels for the north-west and north-east corners of Dallam and northern Sherman counties. In general, trends in the computed groundwater levels closely followed those in the measured historical groundwater levels.

A statistical analysis was performed to quantify differences between computed and historical groundwater levels by comparing the results found for the predevelopment period (Figure 5). The root mean square error was 10.5 meters, which corresponds to a normalized root mean square area of 3%. All compared values were located within the 95% confidence interval, and these results are indicative of good matching for the model.

Calibration for the Exploitation Period (1951–2000)

Comparison of predicted groundwater levels against historical data for the exploitation period (Figure 6A) produced a coefficient of determination of 0.97, and 28 data points were outside of the 95% confidence interval. Sixteen outliers were below the 95% lower limit (underestimation), and 12 data points were above the 95% upper limit (overestimation). Year 1953 presented a set of outliers of underestimated groundwater levels (14 out of 16) and none for the overestimated outliers. The period of 1952–1956 was a sequence of dry years (Dutton et al. 2001). Year 1960 presented half of the total number of overestimated outliers and none of the underestimated groundwater levels. Consequently, predicted trends in the groundwater levels for 1960 highly deviated from that in the measured data presenting differences up to 150 meters between observed and computed groundwater levels for stations 239101 and 246701 (see the 2 most left points for year 1960 in Figure 6B). The period 1956–1960 registered a consistent increase in precipitation through the time that peaked in 1960 in the 4-county area, which partially explains the overestimation of groundwater levels for 1960. Dutton et al. (2000) reported overestimation of registered groundwater levels by more than 45 meters while calibrating a regional model that included eastern Dallam County between 1959 and 1967. Outcomes from this study confirmed that groundwater levels for this period and for stations 239101 and 246701 should be

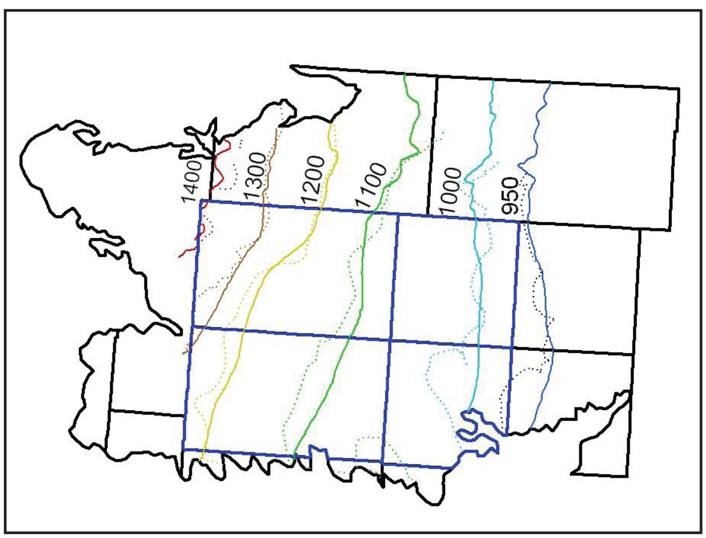

Figure 4. Historical (continuous lines) and simulated (dotted lines) groundwater levels (meters above the mean seal level) after calibrating for the predevelopment period.

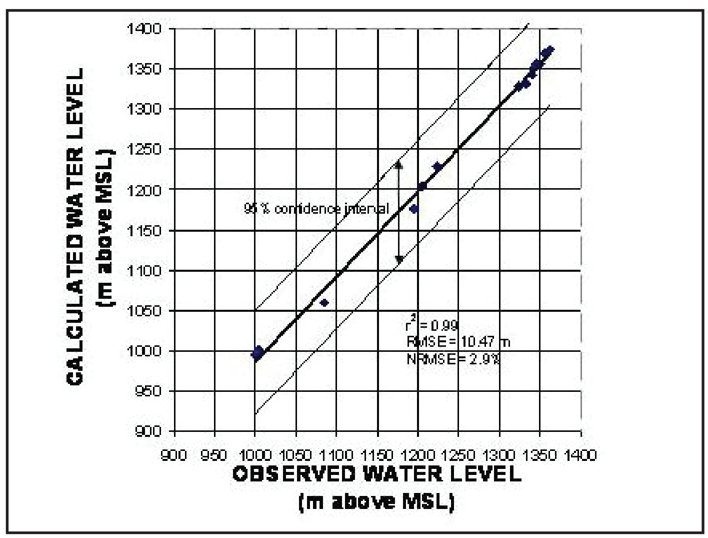

Figure 5. Calibration results for the predevelopment period (before 1950) showing 95% confidence interval and main statistics.

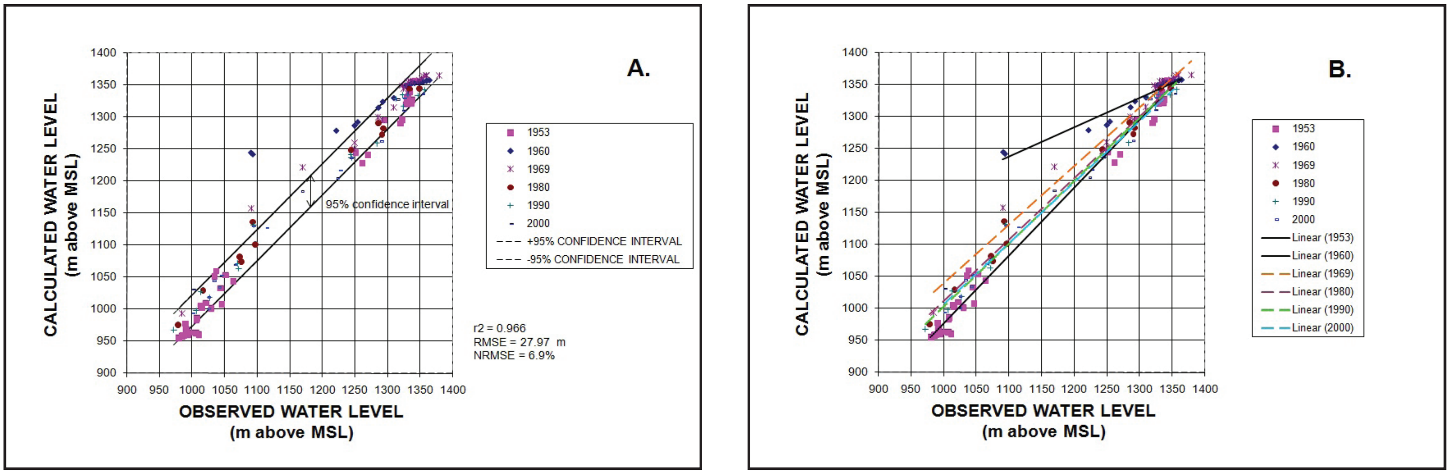

Figure 6. Calibration results for the exploitation period showing correlation between observed and calculated water levels.
A. 95% confidence interval and statistics. **B.** Trend by year.

used with precaution for calibration of future models.

Other overestimation outlier values from stations 246701 and 251501, both located in Dallam County, belonged to year 1969 (Figure 3). Station 239101, located in Dallam County, produced overestimation outliers for years 1960, 1980, 1990, and 2000. It is noteworthy that all stations listed are located in Dallam County. Station 333302, located in Sherman County, produced 1 overestimation outlier for the year 2000. Overall performance for calibration yielded a root mean square error of 28.0 meters and normalized root mean square error of 7% for the exploitation period, indicating that calibration results are acceptable for this study. Table 2 presents a summary for the multiple-year statistics.

Validation for the Exploitation Period (2001–2007)

Validation results demonstrated a strong correlation between calculated groundwater levels and observed levels with a coefficient of determination of 0.98 for the period of 2001–2007, as shown in Figure 7. A root mean square error of 15.5 meters and a normalized root mean square error of 4.3% were computed by comparing predicted groundwater levels with historically registered levels for the same period. The result in the time series with the lowest normalized root mean square error was year 2004 with 4.2%, and the highest magnitude was 5.0% for the year 2003.

Outliers were identified as resulting from 3 specific monitoring stations out of 22 stations used for analysis. Two stations (239101 in Dallam County and 333302 in Sherman County) are located close to the Texas-Oklahoma state boundary, and station 609202 is in central Moore County (Figure 3). The model over-predicted groundwater levels for 2 stations close to the state borderline and under-predicted the groundwater level for the station in Moore County. Station 239101 corresponded to the area located in eastern Dallam County with registration inconsistency for the period of 1959–1967.

Differences between estimated and calculated groundwater levels for over-prediction outliers ranged between 29 meters (station 333302) and 40 meters (station 239101) and between 23 meters and 26 meters for under-prediction outliers (both at

Table 2. Calibration period evaluation showing statistics for correlation coefficient and standard errors for multiple years: Predevelopment Period.

Year	Total Observations	r²	RMSE (m)	NRMSE (%)
1953	41	0.99	23.5	6.3
1960	20	0.95	53.4	19.5
1969	22	0.97	22.7	5.8
1980	12	0.99	15.5	4.2
1990	16	0.99	14.2	3.7
2000	20	0.98	16.5	4.7
All years	131	0.97	28.0	6.9

Table 3. Validation period evaluation showing statistics for correlation coefficient and standard errors for multiple years; Exploitation Period.

Year	Total Observations	r^2	RMSE (m)	NRMSE (%)
2001	19	0.98	15.6	4.8
2002	16	0.98	14.8	4.5
2003	16	0.98	16.4	5.0
2004	16	0.99	13.9	4.2
2005	14	0.98	16.8	4.8
2006	13	0.98	14.6	4.9
2007	17	0.98	16.2	4.6
All years	111	0.98	15.5	4.3

station 609202). Presence of these outliers at specific locations is indicative of low performance of the model in these particular areas. Table 3 presents statistics for the validation period. The correlation coefficients were high showing strong correlation between model results and historical data. In addition, normalized root mean square errors were less than or equal to 5% for each of the validation years, which are indicators of satisfactory model performance.

Impacts of Existing Agricultural Management Practices on Future Groundwater Levels

Simulated groundwater levels in the Ogallala Aquifer were depicted for year 2060 (Figure 8) by calculating groundwater drawdown for a 50-year period (2010–2060) in the future. Groundwater drawdown was computed as the difference between 2010 and 2060 groundwater levels to represent conditions for 2060 relative to 2010. Additionally, a grid image was created using the Kriging interpolation technique for visualizing groundwater drawdown to show the relative change in groundwater levels in the study area (Figure 9). If aquifer exploitation continues constantly at the current rate during the next 50 years, about 9% of the 4-county study area would experience groundwater depletion greater than 30 meters, and 2% of the area would experience groundwater depletion greater than 50 meters in 2060. Most of these areas are located in Hartley County. Of that area, 22% will experience depletion greater than 30 meters, and 5% of the county will experience depletion greater than 50 meters. Consequently, over the next 50 years, groundwater levels are predicted to deplete a maximum of 75 meters and 80 meters in the eastern and northwestern parts of Hartley County, respectively. In Dallam County, 7% of its area will experience depletion greater than 30 meters. Bright areas in Figure 9 are indicative of areas with larger potential for groundwater depletion.

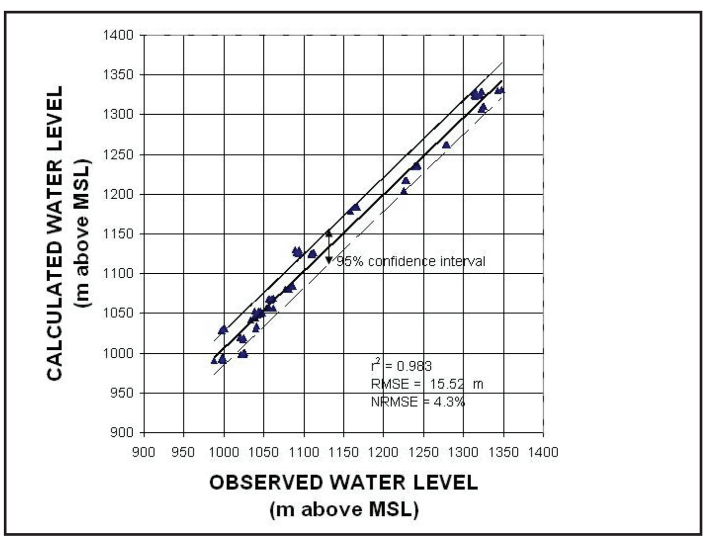

Figure 7. Validation results showing correlation between observed and calculated water levels, 95% confidence interval, and statistics.

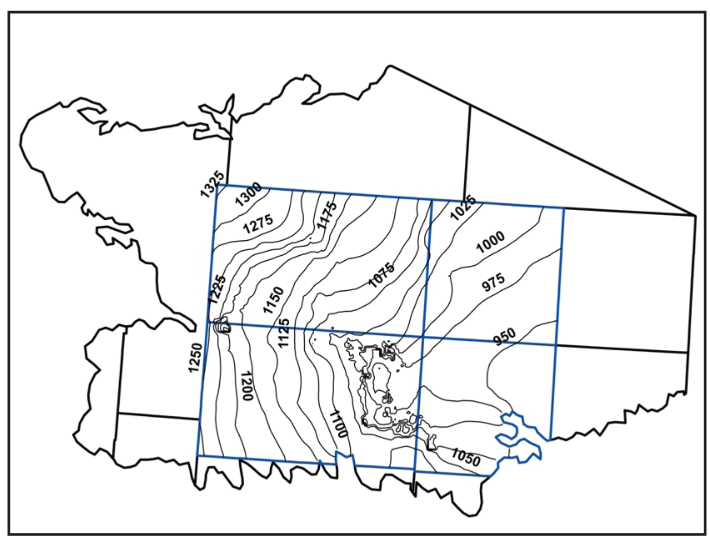

Figure 8. Predicted groundwater levels for 2060 (meters above the mean sea level).

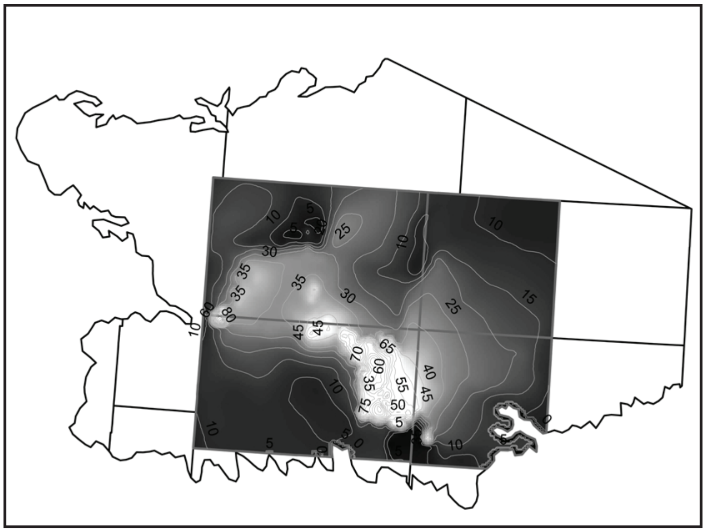

Figure 9. Simulated groundwater drawdown (meters) for applying current aquifer exploitation during the period 2010–2060.

SUMMARY AND CONCLUSION

A groundwater model for the 4-county study area (Dallam, Sherman, Hartley, and Moore counties) in the northwestern Texas High Plains underlying the Ogallala Aquifer region was developed, calibrated, and validated using observed groundwater-level data. The conceptual groundwater model was developed for this purpose. Hydraulic conductivity and recharge rates were most sensitive to predicted groundwater levels and were adjusted in calibrating the model. Performance statistics indicated that trends in the simulated groundwater levels closely followed those in the observed historical groundwater levels in the underlying Ogallala Aquifer.

The model was validated by comparing predictions against historical groundwater levels for the period 2001–2007. The conceptual model and the parameters obtained from the calibrated model were not modified during the validation period. Validation results yielded coefficients of determination greater than 0.97 and normalized root mean square values lower than and equal to 5.0%, indicating excellent agreement between the predicted and observed groundwater levels.

Two zones in the study area were identified as future drying-out zones if the current aquifer exploitation continues at the same rate during the next 50 years. These areas are located in the eastern and northwest portions of Hartley County. This calibrated groundwater model is expected to be used for evaluating the different agricultural management policy scenarios being debated (Amosson et al. 2008) for groundwater levels in the period 2010–2060.

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